Searching for Extra Dimensions in High Energy Cosmic Rays

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We present a study of the decay of an intermediate mini black hole at the first impact of a cosmic ray particle with the atmosphere, in the context of D-brane world scenarios with TeV scale gravity and large extra dimensions. We model the decay of the black hole using the semiclassical approximation and include the corrections coming from energy loss into the bulk. Extensive simulations show that mini black hole events are characterized by essentially different multiplicities and wider lateral distributions of the air showers as a function of the energy of the incoming primary, as compared to standard events. Implications for their detection and some open issues on their possible discovery are also briefly addressed.

1. INTRODUCTION

At a cursory look, the inclusive cosmic ray spectrum, which has been measured over a wide range of energy, seems to be pretty simple in its functional shape, characterized by a (fast-falling) power-like behaviour over a huge energy range. Several mysteries may be hiding behind this apparent simplicity. Two of these mysteries, which have been puzzling theorists and experimentalists alike for several decades, and have been extensively discussed in this Symposium, are the knee (10^{15} eV) and the ankle (10^{19} eV). A long debate which has spurred from these observations has not reached any final conclusions as to the origin of the peculiar spectral dependence measured in these regions. Physics at the knee may involve, according to some interesting proposals, a critical behaviour of the QCD pomeron [1], or, alternatively, disoriented chiral condensates and production of strangelets or other exotics, while the existence or the absence of the GZK cutoff [2] still needs to be completely assessed. Evading the cutoff using string relics [3],[4] has also been proposed as an interesting possibility.

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On the other hand, recent formal suggestions from string theory and gauge theory [5] lead to the exciting possibility of a brane picture of our world, with a gravity scale lowered from 10^{19} GeV down maybe to a fraction of a TeV and with the possibility of envisioning exotic new scenarios where “black hole resonances” might form even at colliders such as the LHC [6]. In cosmic ray physics, in particular, the energy available at the impact of the primaries with the atmosphere can be very large and up to several hundreds of TeVs, and this points favourably towards a possible test of these new scenarios [7].

We have tested the implications of this hypothesis for cosmic ray air showers, by studying, in particular, the lateral distributions and the multiplicities of events mediated by an intermediate black hole. Here we provide a brief summary of our results, while a detailed analysis can be found in [8].

2. MINI BLACK HOLES IN COSMIC RAYS

Various studies of mini black hole production at the LHC have been pulished in the last few years (see [8] for a rather complete list of references). At the same time analytical and nu-

merical studies of greybody factors and the formation of trapped surfaces in extra dimensional models have been able to provide grounds for the experimental searches: in the context of the brane-world scenario black holes will form copiously at hadron colliders, in events characterized by a large multiparticle multiplicity and a "fireball" structure, features which would make this black hole intermediate state look quite distinct from other ordinary resonances.

Mini black holes form, according to Thorne's hoop conjecture (see [8] and references therein), when the energy in the center of mass of a collision is concentrated into a region of radius smaller than the corresponding Schwarzschild radius. The process may be accompanied by a sizeable amount of gravitational energy loss, with a collision which can be characterized by the scattering of two gravitational shock waves of Aichelburg-Sexl type at a small impact parameter. The so-formed black hole decays democratically mostly on the brane (our world) into all the fundamental states of the standard model model or of the supersymmetric standard model, if supersymmetry is also open at that energy scale.

The analysis that we have performed is not based on a Monte Carlo modeling of the decay of the black hole [9], rather we write down and compute the istantaneous parton and lepton emissions of the decay of the black hole using a multinomial probability distribution for the hadronization of a given parton, and using suitable fragmentation functions. These are defined via a renormalization group evolution up to the mean energy of the immediate decay products of the black hole evaporation, which is given by the ratio M_{BH}/N of the black hole mass M_{BH} divided by the average number N of particles produced in such a decay, which in turn is determined in the semiclassical approximation by the entropy of the black hole.

3. A MODEL FOR A MINI BLACK HOLE DECAY

As stated above, mini black holes will be produced in the collision of any primary cosmic ray particle of appropriate energy with a quark or gluon of a nucleon in the atmosphere. Such a collision may lead to the formation of trapped surfaces and of an event horizon, whose size can be of the order of 10^{-3} fm for a fundamental gravity scale M_* of the order of a TeV. A spherical s-wave forms due to the fragmentation of the black hole and the number of states emitted during the decay is computed according to a standard formula for the multiplicities [6], which depends on the number of extra dimensions n. We work in $D = 4 + n$ spacetime dimensions.

We compute the properties of the decay products, after hadronization, by simulating a sequence of uncorrelated air showers using CORSIKA/SIBYLL [10,11] and compare the results of the multiplicities and the lateral distributions of the various components with benchmark simulations of standard events. Other hadronization models are also available in CORSIKA, for instance QGSJET [12].

4. RESULTS

Simulations of observables of the type discussed in [13] have been performed at a small cluster. We have summarized in 4 figures the most salient results of our studies, where we try to distinguish between standard (benchmark) events and black hole mediated events. We plot in Fig. 1 the total particle multiplicity measured at detector level (5000 m) assuming an impact at 5500 m (with a depth $X = 517\ g/cm^2$); a similar simulation at a higher altitude of 15000 m (with a depth $X = 124\ g/cm^2$) is shown in Fig. 2. At energies of the order of 1000 TeV, relevant to the Centauro events, the total multiplicity for $n = 4$ is around 100, for a black hole which evaporated 500 meters above the detector. A black hole produced closer to the detector will obviously lead to fewer particles in the shower, an overall picture consistent with the Centauro observations. Notice also that the multiplicites of black hole events are lower than in the standard events roughly by a factor of 10 in the "low" energy region, while they are larger also be a factor of 10 for energies around the GZK cutoff. These differences tend to become less pronounced for higher altitudes of the initial impact.

As we have explained in [8], a shortcoming of

CORSIKA is that the program is not able to provide a neutrino primary, and for this reason we have used as benchmarks simulations of proton-proton collisions with the same energy and at the same altitude of the signal black hole events. For this reason, the multiplicities of the benchmark events provide an upper bound for the multiplicities of a real event, since hadronic events have clearly larger multiplicities compared, for instance, to neutrino events. As we increase the altitude (Fig. 2) benchmark events and black hole events have similar slopes and intercepts, with minor differences. Independently of the altitude, black hole events are characterized by wider lateral distributions (Figs. 3 and 4) compared to the benchmark result. This is due to the fireball structure of the black hole event, with its original s-wave emission. Our results, of course, rely on a semiclassical picture of the particle emission by the black hole, given by the Hawking formula, and we have corrected for gravity loss in the bulk as well.

We summarize by saying that an analysis of lateral distributions and total multiplicities as a function of energy show a simple linear behaviour (in a log/log scale plot) and measurement of these observables and study of their correlation will be useful criteria to discern among various models for the underlying interactions.

5. PERSPECTIVES

With AUGER being now operational [14], we do expect that a systematic analysis of extensive air showers will provide some evidence, in the near future, for excluding or discovering a low gravity scale, based on experimental data. This will probably render the field more mature from the phenomenological side. It is also likely that most of these studies will not be conclusive, in this respect, but we will be able to set an improved lower bound on the value of M_*, the low gravity scale, which, unfortunately, is not a prediction but just a parameter of the theory.

Note Added

After completing this investigation we have been informed by D. Heck that a new version of CORSIKA has been released which allows to treat neutrino as primaries in the simulations. As we have discussed above, the use of neutrino as a benchmark simulation should only render more remarked the differences between black hole events and benchmark events in the characteristics of the air showers that have been studied here.

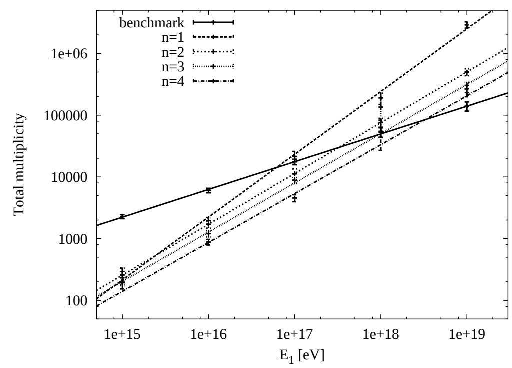

Figure 1. Plot of the total particle multiplicity as a function of E_1 The first interaction is kept fixed at 5500 m (517 g/cm^2) and the observation level is at 5000 m (553 g/cm^2). We show in the same plot the benchmark result (with a proton as a primary) and the mini black hole result for a varying number of extra-dimensions n.

REFERENCES

1. A.R. White, hep-ph/0405190; Proceedings of the 8th International Symposium on Very High Energy Cosmic Ray Interactions, Tokio (1994); hep-ph/0409181.
2. K. Greisen, *Phys. Rev. Lett.* **16** (1966) 748; G.T. Zatsepin and V.A. Kuzmin,*Pisma Zh. Eksp. Theor. Fiz.* **4** (1966) 114.
3. S. Chang, C. Corianò and A.E. Faraggi *Nucl. Phys.* **B477** (1996) 65.
4. C. Corianò, A.E. Faraggi and M. Plümacher, *Nucl. Phys.* **B614** (2001) 233.
5. N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. **B429**, 263 (1998), hep-ph/9803315; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. **B436**, 257 (1998), hep-ph/9804398;

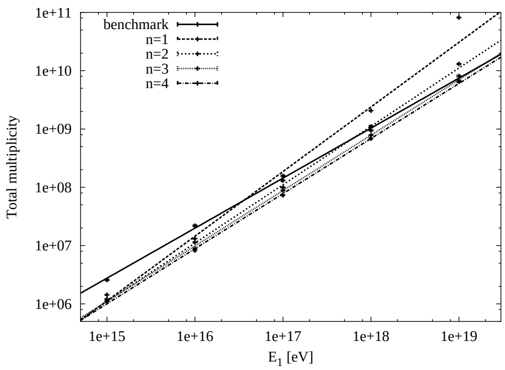

Figure 2. As in Fig. 1, but this time the first interaction occurs at 15000 m (124 g/cm^2).

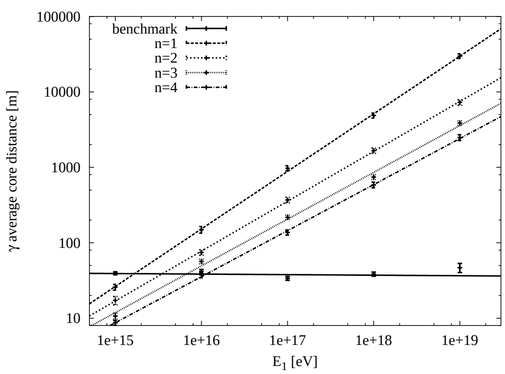

Figure 3. Plot of the the average distance R of the core of the shower of photons as a function of E_1. The first interaction is kept fixed at 5500 m (517 g/cm^2).

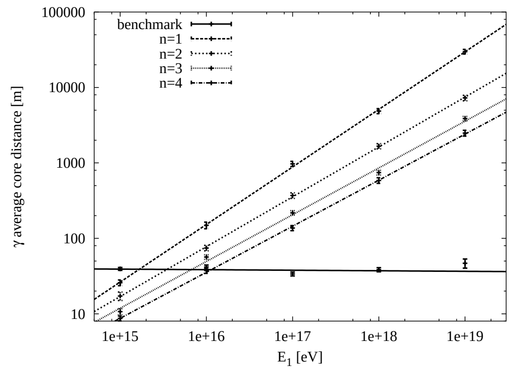

Figure 4. As in Fig. 3, but this time the first interaction occurs at 15000 m (124 g/cm^2).

L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999), hep-ph/9905221; L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 4690 (1999), hep-th/9906064.

6. S. Dimopoulos and G. Landsberg, Phys. Rev. Lett. **87**, 161602, (2001).
7. A. Mironov, A. Morozov and T.N. Tomaras, hep-ph/0311318.
8. A. Cafarella, C. Corianò and T.N. Tomaras, hep-ph/0410358.
9. E. Ahn, M. Ave, M. Cavaglià and A.V. Olinto, Phys. Rev **D68**, 043004, (2003).
10. D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz and T. Thouw, "CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers", FZKA 6019, (1998).
11. R.S. Fletcher, T.K. Gaisser, Paolo Lipari, Todor Stanev, Phys.Rev.**D50**, 5710, (1994).
12. N.N. Kalmykov, S.S. Ostapchenko, A.I. Pavlov, Nucl. Phys. B. (Proc. Suppl.) **52B**, 17, (1997).
13. A. Cafarella, C. Corianò and A.E. Faraggi, Int.J.Mod.Phys.**A19** 3729, (2004).
14. The AUGER collaboration, *Nucl. Phys. Proc. Suppl.* **110**, 487, (2002).